DEVELOPMENT OF A MULTI-SCALE FRAMEWORK FOR MAPPING GLOBAL EVAPOTRANSPIRATION

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ABSTRACT (100-150 WORDS)

As the world's water resources come under increasing tension due to dual stressors of climate change and population growth, accurate knowledge of water consumption through evapotranspiration (ET) over a range in spatial scales will be critical in developing adaptation strategies. Remote sensing methods for monitoring consumptive water use (e.g, ET) are becoming increasingly important, especially in areas of significant water and food insecurity. One method to estimate ET from satellite-based methods, the Atmosphere Land Exchange Inverse (ALEXI) model uses the change in mid-morning land surface temperature to estimate the partitioning of sensible and latent heat fluxes which are then used to estimate daily ET. This presentation will outline several recent enhancements to the ALEXI modeling system, with a focus on global ET and drought monitoring.

***Index Terms*—** Evapotranspiration, remote sensing, water resources, drought

1. INTRODUCTION

The monitoring of evapotranspiration can be assessed through various modeling or remote-sensing based methods or models. Prognostic land-surface models require accurate a priori information about global precipitation patterns, soil moisture storage capacity, groundwater tables, and artificial controls on water supply (e.g., irrigation, dams and diversions, inter-basin water transfers, etc.) to reliably link rainfall to evaporative fluxes. In contrast, diagnostic estimates of ET can be generated, with no prior knowledge of the surface moisture state, by energy balance models using thermal-infrared (TIR) remote sensing of land-surface temperature (LST) as a boundary condition. The LST inputs carry valuable proxy information regarding soil moisture and its effect on soil surface evaporation and canopy stresses limiting transpiration.

2. MODEL METHODOLOGY

The ALEXI surface energy balance model [1,2] was specifically designed to minimize the need for ancillary meteorological data while maintaining a physically realistic representation of land-atmosphere exchange over a wide range in vegetation cover conditions (Fig. 1). It is one of few land-surface models designed explicitly to exploit the high temporal resolution afforded by geostationary satellites. Surface energy balance models estimate ET by partitioning the energy available at the land surface (RN – G, where RN is net radiation and G is the soil heat conduction flux, in Wm-2) into turbulent fluxes of sensible and latent heating (H and λE, respectively, Wm-2): The land-surface representation in ALEXI model is based on the series version of the two-source energy balance (TSEB) model of [3], which partitions the composite surface radiometric temperature, TRAD, into characteristic soil and canopy temperatures, T_S and T_C, based on the local vegetation cover fraction apparent at the thermal sensor view angle. With information about TRAD, LAI, and radiative forcing, the TSEB evaluates the soil (subscript 's') and the canopy ('c') energy budgets separately, computing system and component fluxes of net radiation ($RN=RN_C+RN_S$), sensible

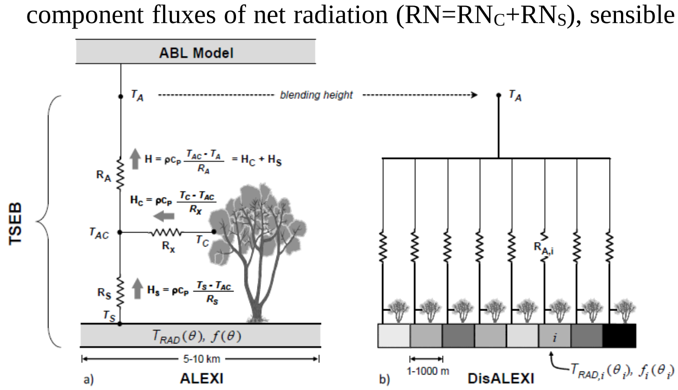

Figure 1. Schematic for the ALEXI modeling system (left) and DisALEXI high-resolution modeling system (right).

and latent heat ($H=H_C+H_S$ and $\lambda E=\lambda E_C+\lambda E_S$), and soil heat (G). Importantly, because angular effects are incorporated into the decomposition of TRAD, the TSEB can accommodate TIR data acquired at off-nadir viewing angles by geostationary satellites. The TSEB has a built-in mechanism for detecting thermal signatures of stress in the soil and canopy. An initial iteration assumes the canopy transpiration (λE_C) is occurring a potential (non-moisture limited) rate, while the soil evaporation rate (λE_S) is computed as a residual to the system energy budget. If the vegetation is stressed and transpiring at significantly less than the potential rate, λE_C will be overestimated and the residual λE_S will become negative. Condensation onto the soil is unlikely midday on clear days, and therefore $\lambda ES<0$ is considered a signature of system stress. Under such circumstances, the λE_C is iteratively down-regulated until $\lambda E_S\sim 0$ (expected under dry conditions).

For regional-scale applications of the TSEB, the air temperature boundary condition, T_A in Fig. 1 must be specified at the spatial resolution of the geostationary thermal data (typically 3-10 km). Due to localized land-atmosphere feedback, this cannot be accomplished with adequate accuracy using standard synoptic measurements, with typical spacing in the US of 100 km. To overcome this limitation, the TSEB has been coupled with an atmospheric boundary layer (ABL) model, thereby simulating land-atmosphere feedback internally. In the ALEXI model, the TSEB is applied at two times during the morning ABL growth phase (~ t_1=1.5 and t_2=5.5 h after local sunrise), using TIR data obtained from a geostationary platform. Energy closure over this interval is provided by a simple slab model of ABL development [4], which relates the rise in air temperature in the mixed layer to the time-integrated influx of sensible heat from the land surface. As a result of this configuration, ALEXI uses only time-differential temperature signals, thereby minimizing flux errors due to absolute sensor calibration and atmospheric and emissivity corrections [5]. The primary radiometric signal is the morning surface temperature rise, while the ABL model component uses only the general slope (lapse rate) of the atmospheric temperature profile [1], which is more reliably analyzed from synoptic radiosonde data than is the absolute temperature reference.

3. EXPLOITING TWICE-DAILY POLAR OBSERVATIONS FOR GLOBAL ET MAPPTING

Until recently, ALEXI ESI has been limited to areas with high resolution temporal sampling of geostationary sensors. The use of geostationary sensors makes global mapping a complicated process, especially for real-time applications, as data from as many as five different sensors are required to be ingested and harmonized to create a global mosaic. However, our research team has developed a new and novel method of using twice-daily observations from polar-orbiting sensors such as MODIS and VIIRS to estimate the mid-morning rise in LST that is used to drive the energy balance estimations within ALEXI. This allows the method to be applied globally using a single sensor (in this case, initially MODIS with a planned transition to VIIRS) rather than a global compositing of all available geostationary data. Other advantages of this new method include the higher spatial resolution provided by MODIS and VIIRS and the increased sampling at high latitudes where oblique view angles limit the utility of geostationary sensors. Three different TIR data feeds (see Fig. 2) will be ingested to provide LST data over the ESI period of record (March 2000 to present): MODIS Terra (March 2000 to present); MODIS Aqua (July 2002 to present) and NPP VIIRS (October 2012 to present). Figure 1 shows how the ALEXI sampling window relates to twice daily observations from

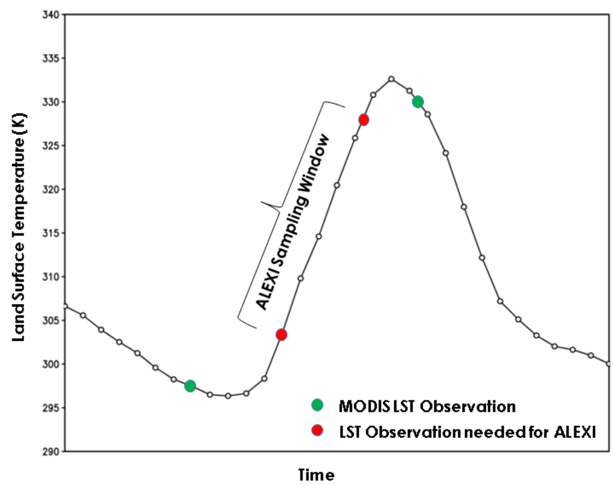

Figure 2. Schematic showing the relationship between twice-daily observations of LST from polar orbiting sensors (e.g., MODIS, VIIRS) and the ALEXI/ESI sampling window used to calculate the mid-morning rise in LST.

MODIS or VIIRS (Anderson et al. 2015; Hain et al. 2016). The twice daily observations are related to the mid-morning rise needed by ALEXI using a rule-based regression model generated with the Cubist software package (RuleQuest). The following variables are used in the regression methodology: (1) MODIS or VIIRS day-night LST difference; (2) MODIS or VIIRS day LST; (3) MODIS or VIIRS night LST; (4) leaf area index; and (5) topographic variability. Global 0.05° time series for each TIR sensor will be generated over the time period they are available. However, differences will exist between the three LST time series. For example, Terra provides an LST retrieval around 10:30 am/pm local time, while Aqua and VIIRS have overpass times at 1:30 am/pm local time. Additionally, algorithm differences exist between MODIS (Terra/Aqua) and VIIRS LST products. A bias correction scheme will be

implemented to harmonize morning temperature rise signals obtained from each TIR data source (note that ALEXI and ESI are relatively insensitive to errors in absolute temperature, only depending on the morning rate of LST rise). The bias correction will exploit a significant data overlap period (2003-2005 for Terra and Aqua overlap; 2013-2015 for Aqua and VIIRS overlap) between the three LST time series to minimize the differences and maintain data continuity over the period of record to be used to compute ESI. Improvements to the spatial resolution of the thermal infrared wavelengths on the VIIRS instrument, as compared to MODIS (375-m VIIRS vs. 1-km MODIS), allows for a much higher resolution ALEXI product than has been previously available. Therefore, recent developments have been to generate 375-m ALEXI ET products over several pilot regions (e.g. western US and the MENA region). Figure 3 shows the annual evapotranspiration (mm) over a section of the Middle East for 2015. The monitoring of consumptive water use over regions where significant groundwater pumping for irrigation is employed is important to accurately quantify the efficiency of water use in the region.

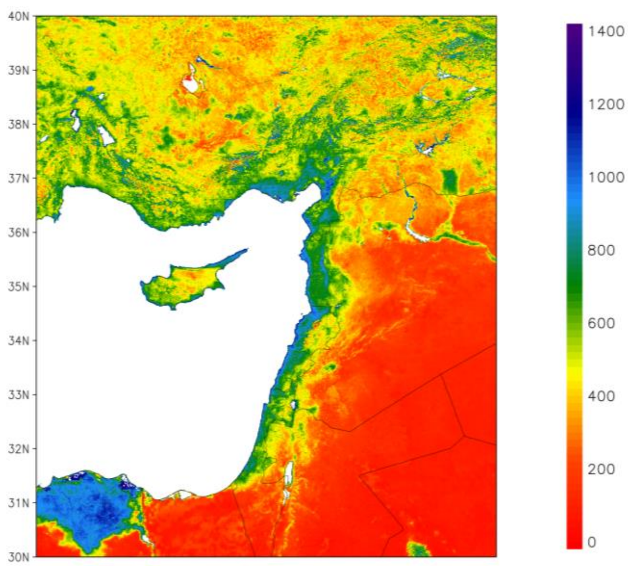

Figure 3. Example of the 375-m VIIRS ALEXI ET (mm) product for 2015.

4. APPLICATIONS FOR GLOBAL MONITORING OF DROUGHT AND VEGETATION STRESS

The Evaporative Stress Index (ESI) represents anomalies in the ratio of actual-to-potential ET (f_{PET}), generated with the thermal remote sensing based Atmosphere-Land Exchange Inverse (ALEXI) surface energy balance model (Anderson et al. 1997; 2011). The LST inputs to ESI have been shown to provide early warning information about the development of stress (Anderson et al. 2013; Otkin et al. 2013; 2015), with stress-elevated canopy temperatures observed well before a decrease in "greenness" is detected in remotely sensed vegetation indices. Whereas many drought indicators based on precipitation or atmospheric conditions capture meteorological drought, the ESI is one of few indicators of agricultural drought that reveals actual vegetation stress conditions realized on the ground. This distinction is particularly important for the agricultural sector where human activity can alter how the drought is actually affecting crop health (e.g., through irrigation, use of drought-resistant crop varietals, etc.). Not all meteorological droughts develop into an agricultural drought, and having indicators specifically related to crop vegetation stress is imperative for improved decision-making by agricultural stakeholders.

As a diagnostic indicator of actual ET, the ESI requires no information regarding antecedent precipitation or soil moisture storage capacity - the current available moisture to vegetation is deduced directly from the remotely sensed LST signal. This signal also inherently accounts for both precipitation and non-precipitation related inputs/sinks to the plant-available soil moisture pool (e.g., irrigation, tile drainage; Hain et al. 2015), which can modify crop response to rainfall anomalies. Independence from precipitation data is a benefit for global agricultural monitoring applications due to sparseness in existing ground-based precipitation networks, and time delays in public reporting. Even as satellite precipitation monitoring has closed some of the observational gaps, these data are usually provided at coarse resolution with accuracy dependent extensive calibration with ground-based precipitation estimates. Additionally, the ESI also provides an important distinction from drought indicators that focus on atmospheric demand which signal the potential for stress but provide no direct link to the onset of actual vegetation stress. In each of these respects, the ESI and ESI-derived Rapid Change Indices will give stakeholders a unique perspective for assessing impacts of agricultural drought on crop and rangeland productivity at the global scale. A global ESI data product is currently

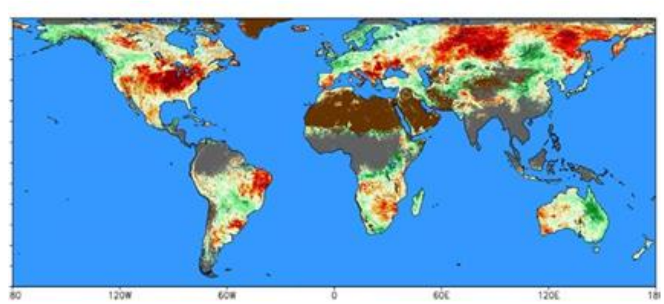

Figure 4. Thermal-only global MODIS/VIIRS 4-week ESI composite product for 1 August 2012. Grey shading denotes regions where significant cloud cover leads to inadequate clear-sky retrievals. Brown shading denotes desert regions where ET is negligible.

being processed in a “near-real-time” prototype towards development of an operational system which will provide weekly global 5-km ESI data products (Figure 4).

5. REFERENCES

[1] Anderson, M. C., J. Norman, G. Diak, W. Kustas, and J. R. Mecikalski, 1997: A two-source time-integrated model for estimating surface energy fluxes using thermal infrared remote sensing, *Remote Sens. Environ*., **60**, 195-216.

[2] Anderson, M. C., W. Kustas, J. M. Norman, C. R. Hain, J. R. Mecikalski, L. Schultz, M. P. González- Dugo, C. Cammalleri, G. d'Urso, A. Pimstein, and F. Gao, 2011: Mapping daily evapotranspiration at field to continental scales using geostationary and polar orbiting satellite imagery, *Hydrol. Earth Syst. Sci*., **15**, 223-239, doi:10.5194/hess-15-223-2011.

[3] Norman, J. M., W. P. Kustas, and K. S. Humes, 1995: A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature, *Agric. For. Meteorol*. **77**, 263-293.

[4] McNaughton, K. G. and T. W. Spriggs, 1986: A mixed-layer model for regional evaporation, *Boundary-Layer Meteorol*., **74**, 262-288.

[5] Kustas, W. P., T. J. Jackson, A. N. French, and J. I. MacPherson, Verification of patch- and regional-scale energy balance estimates derived from microwave and optical remote sensing during SGP97, *J. Hydrometeor*., **2** ,254–273,2001.

[6] Anderson, M. C., C. Zolin, C. R. Hain, K. Semmens, M. T. Yilmaz and F. Gao, 2015: Comparison of satellite-derived LAI and precipitation anomalies over Brazil with a thermal infrared-based Evaporative Stress Index for 2003-2013, *J. of Hydrology*, **526**, 287-302.

[7] Hain, C. R. and M. C. Anderson, 2016: Estimating Mid-morning Change in Land Surface Temperature from MODIS Day/Night Land Surface Temperature, *Geophys. Res. Letts*., In Review.

[8] Anderson, M. C., C. Hain, B. Wardlow, A. Pimstein, J. R. Mecikalski, W. P. Kustas, 2011a: Evaluation of Drought Indices Based on Thermal Remote Sensing of Evapotranspiration over the Continental United States. *J. Climate*, **24**, 2025–2044. doi: 10.1175/2010JCLI3812.1.

[9] Hain, C. R., W. T. Crow, M. C. Anderson and M. T. Yilmaz, 2015: Diagnosing Neglected Soil Moisture Source/Sink Processes via a Thermal Infrared-based Two-Source Energy Balance Model, *J. of Hydrometeor*., **16**, 1070-1086.